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THE ROLE OF GUIDED WAVE ACOUSTO-OPTIC INTERACTIONS IN SINGLE MODE OPTICAL FIBER DESIGN

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ABSTRACT

Several guided acoustic modes are identified to be responsible for the stimulated backward Brillouin scattering (SBBS) in single mode optical fibers (SMF). The dependence of SBBS gain spectra on acoustic properties of SMF is discussed.

1. INTRODUCTION

Stimulated Brillouin backward scattering (SBBS) [1-6] plays a major role in the low loss long haul single mode optical fiber (SMF) transmission system. The maximum transmittable optical power level is principally limited by this nonlinear process [1]. SBBS gain spectra are also of great importance for narrow band fiber optical systems employing frequency division multiplex [3] and gain-introduced techniques [6]. SBBS in SMF can be also regarded as a backward collinear acousto-optic interaction (BCAOI) phenomenon which takes place at very high acoustic frequencies. It has been reported that the acoustic properties of the core and cladding materials of SMF influence the propagation characteristics of guided acoustic waves in a cladded fiber [7-9]. In this theoretical study the BCAOI between guided acoustic modes and guided HE_{11} mode in the fiber core of SMF is analyzed. This analysis allows us to explain the SBBS gain spectra reported in [4]. Furthermore, due to the recent advent of very high frequency acoustic transducers [10] BCAOI with high frequency guided acoustic waves generated by such transducers may be realized in SMF [11] and the role of such configuration in SMF transmission systems is outlined as well.

2. GUIDANCE OF ACOUSTIC WAVES IN CLADDED SMF

A cladded fiber can guide either optical or acoustic or both waves provided that the phase velocity of the core material is lower than that of the cladding. The guidance of acoustic waves in SMF, which has been found to be very intimate to SBBS gain spectra [4], is explained in this section. Let n_i, v_{Si} and v_{Li} be

the refractive index, shear and longitudinal wave velocity respectively; where i = 1 and 2 refer to the core and cladding region respectively. Optical waves are guided in the fiber when $n_1 > n_2$. Since both longitudinal and shear acoustic waves can propagate in a material, a SMF acts as a waveguide for shear (flexural, torsional and radial-axial) and longitudinal modes when $v_{S1} < v_{S2}$ [7,8] and $v_{L1} < v_{L2}$ respectively [9]. Since the propagation characteristics of optical waves in cladded optical fibers is well known, several common terminologies such as dispersion equations are used here to describe the acoustic wave propagation characteristics. SMF is principally under weak guidance which implies δ_n (= $(n_1 - n_2)/n_1$) << 1. Because the amount of dopants in the core or cladding is small, SMF is very likely a weakly guiding acoustic fiber [7-9]. Under weak guidance conditions the dispersion equations are mathematically identical among several types of optical and acoustic modes [12]. This similarity is given in Table 1.

Table 1 Modes With Identical Dispersion Equations

Optical	HE_{nm}	EH_{nm}	TE_{0m}	TM_{0m}
Acoustic	$F_{n,2m-1}$, L_{nm}	$F_{n,2m}$	T_{0m}	R_{0m}

where m =1, 2, 3..... HE and EH, TE and TM are optical hybrid, transverse electrical and transverse magnetic modes respectively; F, L, T and R are acoustic flexural, longitudinal, torsional and radial axial modes respectively. The lowest order longitudinal and flexural modes are L_{01} and F_{11} modes which are predominantly a longitudinal and shear mode respectively [8,9]. If $v_{S1} < v_{S2}$

F_{nm}, T_{0m} and R_{0m} types of waves are well guided. However, the guidance of L_{nm} modes requires not only $v_{L1} < v_{L2}$, but also δ_S (= $(v_{S2} - v_{S1})/v_{S2}$) = 0 and δ_ρ ($|\rho_2 - \rho_1|/\rho_2$) = 0. If $\delta_S \neq 0$ then L_{nm} modes are leaky and and its attenuation is proportional to the $O(\delta_S^2)$ provided that $\delta_\rho \cong 0$ [9].

It is well established that weakly guiding SMF are fabricated mainly by slightly adding some dopants to the host material, pure fused silica (FS) for the core or the cladding or both regions in order to meet optical guidance conditions. Table 2 lists the comparison between the inverse of the refractive index, and longitudinal & shear wave velocities of the doped FS with several different types of dopants; ↑ and ↓ refer to higher and lower than those for pure FS respectively.

Table 2 Comparison of Optical and Acoustic Properties

	GeO_2	P_2O_5	TiO_2	B_2O_3	F_2	Al_2O_3
1/n	↓	↓	↓	↑	↑	↓
v_a	↓	↓	↓	↓	↓	↑

The optical properties in Table 2 are well known, and the acoustic properties have been collected from many published data outlined in Refs.[12,13]. From Table 2 it can be seen that a cladded fiber with GeO_2 doped FS as core and pure FS as cladding will guide both optical and acoustic waves, but that with pure FS as core and B_2O_3 cladding or reverse of this combination will be able to guide only optical or acoustic waves respectively.

3. GUIDED WAVE ACOUSTO-OPTIC INTERACTIONS IN SMF

As stated earlier SBBS can be regarded as a BCAOI, thus it is intuitive that SMF will have stronger SBBS if it also guides the acoustic waves. The SBBS gain spectra in Ref.[4] has proved this hypothesis. Here the formula of the coupling coefficient C of BCAOI which take place between guided acoustic modes and HE_{11} mode are given. Longitudinal types of modes [8] have been identified to be responsible for SBBS in SMF [4] and here several transverse types of acoustic waves involving nonzero C of BCAOI in SMF will also be given.

The coupling coefficient C between two optical waves involved in a BCAOI in SMF is given by

$$C = \frac{\omega \epsilon_0}{4} \int_0^{2\pi} \int_0^{\infty} E_I^{*} \Delta\epsilon E_D \, r dr d\theta \qquad (1)$$

where E_I and E_D are the electric fields of the incident and diffracted optical waves, respectively, $\Delta\epsilon$ is the change of electric permittivity induced by the acoustic wave, ω is the optical frequency and ϵ_0 is the dielectric constant of free space.

For a SMF optical fiber irrespective of the acoustic mode polarization or order, Eqn.(1) can be rewritten as

$$C = C^t + C^z + C^{rz} + C^{r\theta} + C^{\theta z} \qquad (2)$$

where

$$C^t = b \int_0^{2\pi} \int_0^{\infty} n^4 [(p_{11} E_r^2 + p_{12} E_\theta^2) S_{rr} + (p_{12} E_r^2 + p_{11} E_\theta^2) S_{\theta\theta} + p_{12} (E_r^2 + E_\theta^2) S_{zz}] r dr d\theta \qquad (3)$$

$$C^{z} = b\int_0^{2\pi}\int_0^{\infty} n^4 [(p_{12}(S_{rr} + S_{\theta\theta}) + p_{11} S_{zz}] E_z^2 \, r dr d\theta \quad (4)$$

$$C^{rz} = b\int_0^{2\pi}\int_0^{\infty} 4n^4 p_{44} E_r E_z^* S_{rz} \, r dr d\theta \quad (5)$$

$$C^{r\theta} = b\int_0^{2\pi}\int_0^{\infty} 4n^4 p_{44} E_r E_\theta^* S_{r\theta} \, r dr d\theta \quad (6)$$

$$C^{\theta z} = b\int_0^{2\pi}\int_0^{\infty} 4n^4 p_{44} E_\theta E_z^* S_{\theta z} \, r dr d\theta \quad (7)$$

where $b = \omega\epsilon_0/4$ and S_{ij} $(i,j = r, \theta, z)$ are the strain components. It is well known that in a SMF for HE_{11} mode $E_z \propto \cos\theta$, $E_r \propto \cos\theta$ and $E_\theta \propto \sin\theta$. On the other hand when the acoustic mode involved in the BCAOI is L_{nm} type, one concludes that S_{rr}, $S_{\theta\theta}$, S_{zz} and S_{zr} are proportional to $\cos(n\theta)$ whereas $S_{\theta r}$ and $S_{\theta z}$ are proportional to $\sin(n\theta)$ [8,9]. Taking into account these characteristics while calculating the integral shown in Eqns.(3) to (6) one concludes that C is zero except when n=0 or 2. This implies that as far as longitudinal modes are concerned only L_{0m} and L_{2m} can generate BCAOI in SMF. A similar analysis with respect to the transverse types of modes also leads to the conclusion that shear modes, F_{2m}, torsional modes, T_{0m}, and radial-axial modes, R_{0m} have non-zero C for BCAOI. It has been also found out that the lowest order longitudinal mode, L_{01} has the highest C which has been experimentally observed in Ref.[4].

4. THE ROLE OF BCAOI IN SINGLE MODE OPTICAL FIBER DESIGN

In addition to all optical guidance requirements, in order to transmit more optical power in the fiber core, the acoustic properties of the core and cladding of SMF should be arranged in

a way such that the acoustic guidance in the fiber core is minimized thus less amount of SBBS which is a type of BCAOI will take place. Making v_S and v_L of the core higher than those of the cladding respectively is one approach. As the velocity difference increases the SBBS gain decreases. The acoustic impedance, which is the product of the material density and acoustic velocity, of the core is also preferred to be same as that of the cladding. However, in certain applications high efficiency BCAOI including SBBS is desirable [6,5], then good acoustic wave guidance is necessary. Since BCAOI involving L_{01} mode in SMF exhibits the highest efficiency, SMF with $v_{L1} < v_{L2}$ and $\delta_S \cong 0$ and $\delta_\rho \cong 0$ may be preferred. Material properties given in Table 2 could be used as a reference.

Recently optical fiber transmission systems employing stimulated Raman gain (SRG) has become very attractive for certain device applications [1,14,15]. SMF with Ge doped FS as core and pure FS as cladding has been commonly used [14,15] due to the high SRG attributed by the Ge doped core. It is speculated that this system is improved when SBBS is lowered resulting in better transmittance of optical power in the core. However, from Table 1 it can be seen that this particular fiber used in Ref.[15] guides acoustic waves as well, thus higher SBBS is expected. Our suggestion is that if a type or types of dopants can be introduced to the cladding in order to reverse the acoustic guidance conditions, high SRG and low SBBS can be simultaneously obtained.

Due to the recent advent of efficient high frequency acoustic

transducers (up to 96 GHz) [10] BCAOI with acoustic waves generated by using such transducers can take place in SMF [11]. Since acoustic wave frequencies can be varied within the transducer bandwidth, the frequency shift of the back diffracted optical beam may be electronically tuned. In such devices good acoustic guidance in SMF is required. However, because the distance involved with such BCAOI is around 100 microns [11], SBBS is not a concern.

5. CONCLUSIONS

The considerations of guided wave acousto-optic interactions including SBBS for certain SMF transmission systems have been given. It is our belief that acoustic properties which have not been fully considered in the SMF design should play a much more important role.

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